

Technical Analysis of Glass  
Mosaic Tesserae from Amorium

*Mark T. Wypyski*

**S**INCE THE BEGINNING of excavations at Amorium, an important middle Byzantine period site in central Anatolia, hundreds of pieces of glass have been found, including vessels, windowpanes, objects such as bracelets, and mosaic tesserae.<sup>1</sup> This study discusses the results of chemical analyses of a group of tesserae from wall mosaics in the Lower City Church, thought to have been rebuilt circa 900 CE. The tesserae chosen for analysis included red opaque, several shades of opaque green, as well as translucent green, blue, turquoise, and “black,” actually a very dark purple. Also analyzed were some of the gold and silver tesserae, that is, translucent tesserae topped with a layer of gold or silver foil that is underneath an additional thin top layer of translucent glass. The analytical findings for the group of mosaic tesserae discussed here are compared to recent findings for Roman and other Byzantine-period mosaic glass. Several bracelet fragments from the site, as well as one vessel glass fragment, were also analyzed for comparison.

<sup>1</sup> M. A. V. Gill, *Amorium Reports: Finds*, vol. 1, *The Glass (1987–1997)*, with contributions by C. S. Lightfoot, E. A. Ivison, and M. T. Wypyski, BAR International Series 1070 (Oxford, 2002).

## Experimental Details

Small samples of the forty-one tesserae and four bracelet and vessel fragments provided to the author for analysis were removed with the use of a diamond-edged scribe and steel scalpel. Care was taken to sample intact glass from below the outer weathered surfaces. The samples, approximately one cubic millimeter in volume each, were then prepared for analysis by embedding them in epoxy and grinding with silicon carbide paper to expose the sample interiors. The cross sections were polished with cerium oxide, and given a high-vacuum carbon coating for conductivity before analysis. The samples were analyzed over as much of the exposed areas as possible, while avoiding areas of obvious weathering or alteration. The samples were analyzed in the X-ray microanalysis laboratory at The Metropolitan Museum of Art using an Oxford Instruments INCA analyzer equipped with an energy dispersive X-ray spectrometer (EDS) using a Link Pentafet SATW X-ray detector and a Microspec WDX-400 wavelength dispersive X-ray spectrometer (WDS) equipped with LIF, PET, TAP, and LSM 80 crystals, one flow proportional counter, and one sealed proportional counter X-ray detectors. The X-ray analyzers are operated with a LEO Electron Microscopy model 1455 variable pressure scanning electron microscope (VP-SEM). Analyses were performed under high-vacuum conditions at an accelerating voltage of 20 kV, with a beam current of approximately 1 nA and input rate of 2,000 cps used for EDS analysis, and a beam current of approximately 50 nA for WDS analysis.

Weight percentage concentrations of the elements detected were calculated using well-characterized reference glasses and glass standards, including Corning A, B, C, and D and Society of Glass Technology standards 5 to 11. The relative variation in the calculated percentages for the major element oxides for EDS has been estimated to be less than 2 percent for silicon, about 5 percent for sodium, potassium, and calcium, and about 10 percent for magnesium, aluminum, and the metals such as copper and iron. The minimum detection limits (MDL) for most elements with EDS were found to be about 0.1 percent. The MDL for phosphorus and barium, however, were found to be somewhat higher, estimated at approximately 0.2 percent under these operating conditions, while the detection limits of elements such as lead, antimony, and tin were found to be even higher, about 0.5 percent by weight, mainly due to peak overlap problems.<sup>2</sup> The MDL with the wavelength dispersive spectrometer under these operating conditions was estimated to be about 0.01 percent for most of the elements searched for here. The MDL for phosphorus, antimony, and strontium oxides was slightly higher, at about 0.02 percent, whereas lead oxide was estimated at about 0.05 percent. Table 1 provides the quantitative results of the EDS and WDS analyses of the forty-five glass samples, given in oxide weight percentages. The results for the major and minor components 0.5 percent or higher are from EDS analysis; the results listed for the oxides under 0.5 percent are from WDS analysis and are reported to two decimal places.

## Results

The tesserae selected for analysis are representative of the different colors and shades found on site. These were described as dark blue, dark turquoise, light turquoise, dark emerald green, light emerald green, dark yellow-green, light yellow-green, olive green, red, orange-red, black, silver on bottle green, gold on amber cut glass, and gold on amber with molten cover glass. The last group of four tesserae shows evidence of being in a fire, in that the cover glass over the gold appears to have been melted to a rounded shape and is distinguished

opposite page

**Table 1** SEM-EDS/WDS Analyses of Glass Compositions (Weight %)

2 M. Verità, R. Basso, M. T. Wypyski, and R. J. Koestler, "X-Ray Microanalysis of Ancient Glassy Materials: A Comparative Study of Wavelength Dispersive and Energy Dispersive Techniques," *Archaeometry* 36.2 (1994): 241–51.

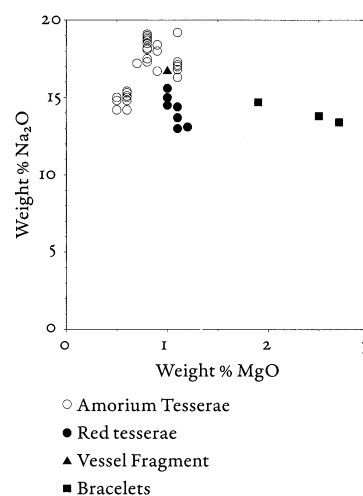
No.	Description	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	Cl	K2O	CaO	TiO2	MnO	Fe2O3	CoO	NiO	CuO	ZnO	As2O3	SrO	SnO2	Sb2O3	BaO	PbO
1	dark blue	18.4	0.9	2.3	64.8	0.15	0.40	0.9	0.6	7.9	0.14	1.3	1.1	0.07	nd	0.10	nd	nd	0.05	0.06	nd	0.04	0.8
2	black 1	18.0	0.9	2.3	64.6	0.12	0.43	0.8	0.7	8.0	0.17	2.6	1.2	nd	nd	0.05	nd	nd	0.07	0.02	nd	0.05	0.30
3	black 2	18.7	0.9	2.2	65.2	0.14	0.40	0.8	0.6	7.8	0.13	2.1	0.9	nd	nd	0.06	nd	nd	0.07	nd	nd	0.06	0.09
4	black 3	18.7	0.9	2.2	64.8	0.22	0.41	0.8	0.6	8.0	0.13	2.2	0.9	nd	nd	0.04	nd	nd	0.07	nd	nd	0.07	nd
5	dark turquoise 1	15.0	0.6	2.7	66.8	0.30	0.14	1.0	0.8	8.6	0.08	0.13	0.5	nd	nd	2.2	0.02	nd	0.04	0.21	nd	0.03	0.6
6	dark turquoise 2	17.5	0.8	2.2	66.8	0.11	0.30	0.8	0.6	7.2	0.12	0.24	0.7	nd	nd	1.8	0.01	nd	0.05	0.18	nd	0.02	0.35
7	dark turquoise 3	17.5	0.8	2.2	67.6	0.15	0.31	0.8	0.6	7.5	0.13	0.35	0.7	nd	nd	1.1	0.01	nd	0.06	0.09	nd	0.02	0.30
8	dark turquoise 4	17.3	0.8	2.3	66.8	0.18	0.41	0.8	0.6	7.5	0.12	0.32	0.7	nd	nd	1.6	0.02	nd	0.07	0.15	nd	0.02	0.40
9	dark turquoise 5	17.2	0.7	2.3	66.8	0.13	0.34	0.9	0.6	7.6	0.10	0.32	0.7	nd	nd	1.6	0.01	nd	0.07	0.13	nd	0.02	0.45
10	dark turquoise 6	14.8	0.5	2.7	69.4	0.20	0.12	1.0	0.7	8.0	0.08	0.05	0.48	nd	nd	1.4	nd	nd	0.04	0.12	nd	0.03	0.32
11	light turquoise 1	18.2	0.9	2.2	68.2	0.14	0.34	0.8	0.6	7.1	0.12	0.11	0.7	nd	nd	0.6	nd	nd	0.04	0.05	nd	0.03	0.17
12	light turquoise 2	18.1	0.9	2.1	68.2	0.14	0.36	0.8	0.6	7.0	0.12	0.11	0.7	nd	nd	0.8	nd	nd	0.04	0.06	nd	0.02	0.22
13	light turquoise 3	18.0	0.9	2.2	68.0	0.11	0.36	0.8	0.5	6.9	0.13	0.12	0.7	nd	nd	0.8	nd	nd	0.05	0.07	nd	0.02	0.19
14	dark emerald green 1	15.4	0.6	2.5	63.4	0.12	0.18	0.9	0.8	7.9	0.08	0.07	0.5	nd	nd	1.2	0.01	nd	0.04	0.8	nd	0.03	5.7
15	dark emerald green 2	14.8	0.6	2.5	63.8	0.13	0.14	1.0	0.8	7.6	0.07	0.09	0.43	nd	nd	1.3	0.01	nd	0.03	0.8	nd	0.03	6.0
16	dark emerald green 3	15.0	0.5	2.5	64.0	0.12	0.11	1.0	0.8	7.7	0.07	0.05	0.40	nd	nd	1.3	nd	nd	0.02	0.8	nd	0.03	5.5
17	dark emerald green 4	14.4	0.6	2.6	64.2	0.14	0.12	0.8	0.9	7.9	0.07	0.06	0.45	nd	nd	1.4	nd	nd	0.02	0.6	nd	0.03	5.7
18	light emerald green	14.2	0.6	2.4	65.4	0.12	0.08	0.8	0.7	7.5	0.06	0.04	0.38	nd	nd	0.9	nd	nd	0.03	0.9	nd	0.03	5.7
19	dark yellow-green 1	15.1	0.6	2.4	64.0	0.16	0.13	0.8	1.2	6.6	0.07	0.03	0.40	nd	nd	0.7	nd	nd	0.03	0.9	nd	0.02	6.9
20	dark yellow-green 2	14.2	0.5	2.4	65.7	0.15	0.10	0.9	0.7	7.6	0.07	0.04	0.41	nd	nd	0.6	nd	nd	0.04	0.8	nd	0.02	6.0
21	light yellow-green 1	15.3	0.6	2.2	65.0	0.08	0.19	0.8	0.6	6.9	0.08	0.06	0.5	nd	nd	0.5	nd	nd	0.03	0.8	nd	0.03	6.5
22	light yellow-green 2	15.1	0.6	2.2	63.4	0.09	0.14	0.8	0.6	6.8	0.06	0.05	0.45	nd	nd	0.5	nd	nd	0.04	1.0	nd	0.02	8.4
23	olive green	16.7	0.9	2.1	60.2	0.08	0.35	0.8	0.6	7.7	0.13	1.4	1.1	nd	nd	0.01	nd	nd	0.05	1.0	nd	0.04	7.0
24	amber with gold 1	17.1	1.2	2.4	65.4	0.10	0.40	0.8	0.7	8.6	0.13	2.0	1.2	nd	nd	0.01	nd	nd	0.09	nd	nd	0.06	nd
25	amber with gold 2	17.0	1.1	2.4	65.3	0.11	0.37	0.8	0.7	8.8	0.15	2.0	1.2	nd	nd	0.01	nd	nd	0.08	nd	nd	0.06	nd
26	amber with gold 3	18.8	0.9	2.1	65.8	0.06	0.43	0.8	0.5	8.2	0.12	1.7	0.8	nd	nd	0.01	nd	nd	0.04	nd	nd	0.04	nd
27	amber with gold 4	19.1	0.9	2.1	65.6	0.06	0.41	0.7	0.5	8.1	0.11	1.7	0.8	nd	nd	0.01	nd	nd	0.05	nd	nd	0.04	nd
28	amber with gold (molten) 1	18.9	0.8	2.2	65.3	0.07	0.41	0.8	0.5	8.3	0.12	1.7	0.8	nd	nd	0.01	nd	nd	0.07	nd	nd	0.04	nd
29	amber with gold (molten) 2	17.3	1.1	2.4	65.2	0.10	0.37	0.7	0.7	8.6	0.13	2.0	1.3	nd	nd	0.01	nd	nd	0.06	nd	nd	0.06	nd
30	amber with gold (molten) 3	19.0	0.9	2.1	65.7	0.07	0.43	0.7	0.5	8.1	0.12	1.6	0.8	nd	nd	0.01	nd	nd	0.06	nd	nd	0.04	nd
31	amber with gold (molten) 4	18.5	0.9	2.1	65.4	0.07	0.43	0.8	0.5	8.5	0.13	1.8	0.8	nd	nd	0.01	nd	nd	0.07	nd	nd	0.04	nd
32	silver on bottle green 1	19.2	1.1	2.3	65.0	0.14	0.36	0.9	0.6	7.8	0.13	1.7	0.9	nd	nd	0.01	nd	nd	0.04	nd	nd	0.06	nd
33	silver on bottle green 2	16.3	1.2	2.5	65.8	0.13	0.36	0.7	0.7	9.0	0.16	1.5	1.6	nd	nd	0.01	nd	nd	0.08	nd	nd	0.04	nd
34	silver on bottle green 3	16.8	1.2	2.6	65.0	0.13	0.44	0.7	0.7	9.6	0.16	1.6	1.1	nd	nd	0.01	nd	nd	0.09	nd	nd	0.05	nd
35	red 1	13.0	1.2	2.4	52.8	0.41	0.30	0.6	1.1	7.5	0.17	1.1	2.5	0.04	0.07	1.7	0.9	0.05	0.07	3.3	nd	0.04	11.2
36	red 2	15.6	1.0	2.3	57.5	0.26	0.30	0.7	1.0	7.6	0.16	1.1	2.2	0.02	0.07	1.7	0.7	0.02	0.05	2.0	nd	0.04	6.0
37	red 3	14.4	1.1	2.3	57.2	0.31	0.30	0.6	1.0	7.7	0.17	1.0	2.6	0.02	0.03	1.3	0.9	0.02	0.05	1.8	nd	0.04	7.5
38	red 4	15.0	1.1	2.3	55.4	0.24	0.32	0.7	0.9	7.4	0.15	1.1	3.2	0.03	0.07	1.9	0.7	0.04	0.04	2.8	nd	0.04	6.8
39	red 5	13.7	1.2	2.5	55.5	0.40	0.27	0.6	1.1	7.9	0.18	1.2	2.4	0.03	0.05	1.3	0.7	0.03	0.08	2.0	nd	0.04	9.0
40	red 6	14.5	1.1	2.3	57.0	0.30	0.34	0.6	1.0	7.5	0.16	1.1	2.4	0.02	0.04	1.4	0.8	0.03	0.08	1.9	nd	0.03	7.5
41	red 7	13.1	1.2	2.4	52.8	0.36	0.26	0.5	1.1	7.4	0.16	1.1	2.5	0.04	0.08	1.6	0.9	0.04	0.03	3.4	nd	0.04	11.2
B1	bracelet red 1	13.8	2.5	2.4	63.2	0.10	0.17	0.20	1.6	10.6	0.10	0.07	3.8	nd	nd	1.3	nd	nd	0.21	nd	nd	0.02	nd
B2	bracelet red 2	13.4	2.7	2.8	61.8	0.08	0.14	0.15	1.6	10.7	0.12	0.07	5.4	nd	nd	1.1	nd	nd	0.21	nd	nd	0.01	nd
B3	bracelet red 3	14.7	1.9	2.3	63.4	0.15	0.20	0.5	1.5	8.5	0.12	0.6	3.0	nd	nd	2.9	0.01	nd	0.11	0.01	nd	0.03	0.25
V1	vessel red	16.7	1.0	3.0	64.5	0.20	0.23	0.8	1.0	7.9	0.19	0.9	1.7	nd	nd	0.27	0.08	nd	0.04	0.30	nd	0.04	1.1

from the other gold-covered tesserae that were described as cut glass. All the tesserae analyzed were translucent except for the reds, emerald greens, and the yellow-greens. Several of the tesserae were initially identified incorrectly due to weathering of the surface. One of the tesserae, identified as opaque light gray-blue in color, was actually a translucent light turquoise covered with a thin gray skin of weathered devitrified glass (table 1, no. 12). This glass, while showing much more deterioration on its surface, was found to be virtually identical in composition to the other two light turquoise tesserae. Weathered surfaces on other tesserae also led to misidentifications. One tessera identified as light turquoise was actually dark turquoise in color (table 1, no. 10), and two others also identified as light turquoise were found to be dark emerald green in color (table 1, nos. 16, 17). One tessera described as being orange-red in color (table 1, no. 41) was actually simply a red tessera covered with a thin yellow-brown skin, and in fact is almost identical in composition to red 1 (table 1, no. 35).

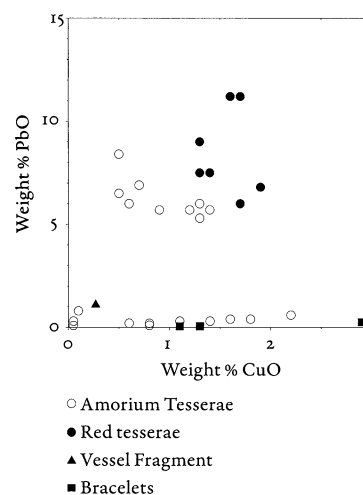
All forty-one of the tesserae analyzed were found to have soda-lime-silica compositions with relatively low levels of magnesia and potash (magnesium and potassium oxides), although they are close to or exceed one percent in many of the glasses, particularly the reds (fig. 1). Soda (sodium oxide) levels varied from about 13 to 19 percent, with the smallest amounts found in the reds. Lime (calcium oxide) for the most part varied from about 7 to 9 percent, with only a few slightly lower or higher. Alumina (aluminum oxide) levels were also relatively high, generally between 2 and 2.5 percent, with only a few slightly higher. Little or no lead oxide was found in the majority of the glasses, although significant amounts were found in the emerald green and yellow-green tesserae, and somewhat larger amounts of lead oxide were found in the reds, up to a maximum value of about 11 percent (fig. 2).

The dark blue tessera was found to contain cobalt oxide as a colorant. A significant amount of iron oxide was also found in the dark blue glass, probably added unintentionally with the source of the cobalt. Although traces of cobalt were also detected in the seven red tesserae, they do not appear to be enough to affect the color in the red opaque glasses, and may have been an unintentional addition with the source of iron used in these glasses. A trace of copper was also found in the blue, but it also does not appear to be enough to affect the color significantly. The turquoise, greens, and reds, however, were all found to contain significant amounts of copper. Copper oxide alone in glass can give it a light blue to turquoise color. The presence of iron in a copper-containing glass tends to shift the color more toward turquoise, as in the dark and light turquoise tesserae here, or even to green, depending on the overall composition and the oxidizing conditions of the melt. In the red tesserae, however, most of the copper is presumably present in the reduced form of cuprite ( $\text{Cu}_2\text{O}$ ) crystals, which serve to render the glass opaque as well as give it the red color. In addition to the copper, the reds were all found to contain large amounts of iron, as well as significant amounts of zinc, tin, and lead. Traces of nickel and arsenic, as well as the cobalt mentioned previously, were also noted in the reds, but not detected in any of the other colors.

The opaque green tesserae were found to contain small amounts of lead and significant amounts of tin as well. High magnification analysis in the SEM revealed the presence of small crystals consisting mainly of lead and tin, in an approximately one to one atomic ratio, which appear to be lead-tin yellow crystals ( $\text{PbSnO}_3$ ). The overall ratio of lead oxide to tin oxide, in weight percent, however, is almost eight to one. Some of the crystals in these greens appeared to be present in the form of tin oxide, rather than lead-tin oxide. Antimony was



**Fig. 1** Comparison of soda and magnesia concentrations for the 41 tesserae and other glasses. Note differences in the magnesia values for the bracelet glasses as compared to the tesserae and the vessel fragment. All SEM micrographs and plots are by the author.



**Fig. 2** Comparison of lead oxide and copper oxide values for the tesserae, vessel and bracelet glasses. Significant amounts of lead were found only in the green and red tesserae.

also looked for, but was not detected in any of the opaque greens or in any of the glasses analyzed in this study. The opaque green glasses, unlike the majority of glasses in this study, were observed in the light microscope and in the SEM to be somewhat heterogeneous, with streaks of clear, low lead glass alternating with higher lead opaque streaks. Spot analyses in the streaks revealed that the tin is associated mainly with the high lead areas. The olive green translucent glass was also found to contain lead and a significant amount of tin as well. As in the greens, lead-tin crystals as well as some tin oxide crystals were found in the glass. Unlike the opaque greens, however, the overall appearance of the glass is translucent, and the greenish color is partly due to the iron oxide present, rather than copper, as none was detected in the glass.

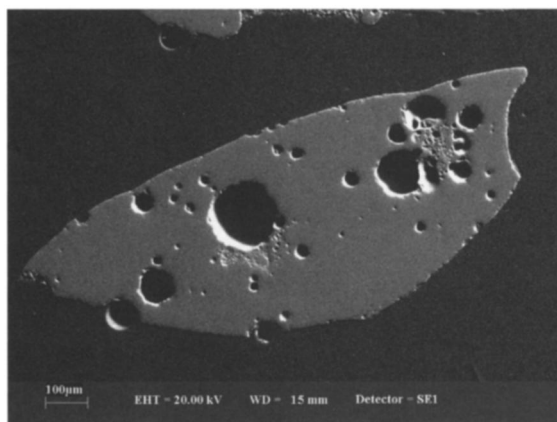
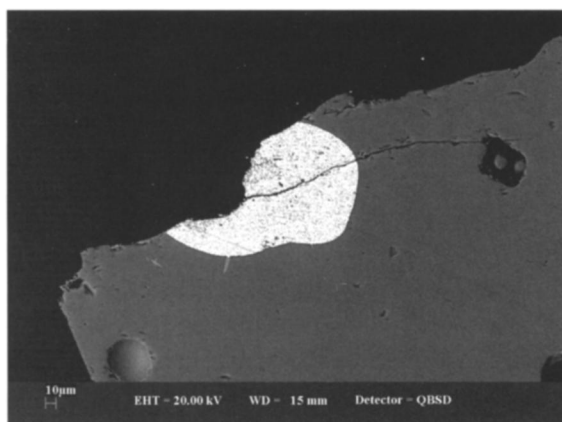
The black tesserae examined by transmitted light were found to be actually dark purple in color, produced by the large amounts of manganese observed in the tesserae. Relatively large black inclusions observed in one of the tesserae (table 1, no. 2) were found to consist mostly of manganese and appear to be a form of manganese oxide, which was not entirely dissolved in the glass, or was perhaps intentionally left to aid in producing the black appearance of the glass (fig. 3). Relatively large amounts of manganese, up to 2 percent, were also found in the amber tesserae with gold foil and the green tesserae with silver foil. The green colors of these tesserae depend not only on the amounts of manganese present but perhaps more importantly on the amount of iron oxide present and the oxidation state of the iron. The green color of the silver-covered tesserae appears to be due to the iron, as no significant amount of copper was found in any of these three glasses. Whereas the green color appears to be due mainly to a mixture of oxidized and reduced iron oxides, the amber color of the gold tesserae may be due to iron sulfide. Analyses of the cover layers of glass over the gold or silver metal leaf showed that they were made from the same glass as the base layers.

The turquoise tesserae were observed to contain many voids or air bubbles in the glass (fig. 4). Small white patches were also noted in some of the turquoise tesserae. These were found to consist mainly of calcium and phosphorus, and may be calcium phosphate from bone or ivory that was added to the glass. Although in transmitted light the turquoise glasses can be seen to be translucent, the bubbles and to some extent the white inclusions give the glasses a cloudy or somewhat opaque look.

Inclusions were discovered in some of the other glasses as well. Relatively large, clear inclusions were noted in many of the greens; EDS analysis revealed that these inclusions were silica ( $\text{SiO}_2$ ) particles. The dark blue tessera was

**Fig. 3** Scanning electron micrograph of a sample of black glass showing one of the large manganese oxide inclusions on the edge of the sample (original magnification 500 $\times$ ).

**Fig. 4** Scanning electron micrograph of a cross-sectioned sample of dark turquoise tesserae showing the many bubbles or voids in the glass as well as two calcium-phosphorus inclusions (original magnification 200 $\times$ ).



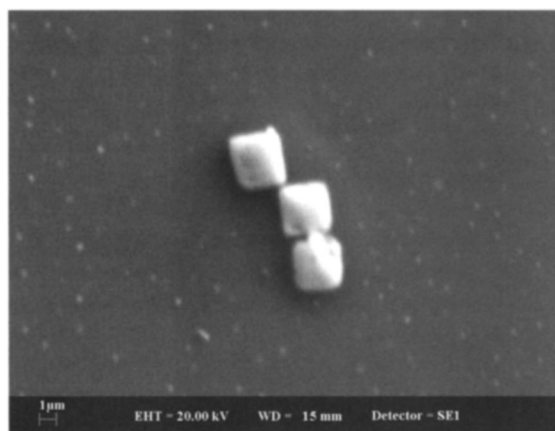
found to contain a number of small round droplets, which consisted of copper and sulfur, possibly in the form of copper sulfide ( $\text{Cu}_2\text{S}$ ). One of the emerald green tesserae (table 1, no. 18) also contained a large round silvery inclusion, which upon analysis was found to consist mainly of lead, possibly lead oxide.

The red tesserae contained by far the most inclusions. In addition to the submicron cuprite crystals that provide the red color, relatively large tin inclusions, cubic or rhombohedral in shape, ranging from about 3 to 20 microns on a side, were noted in all of the red tesserae, although most were in the range of 5 to 10 microns (fig. 5). These appear to consist of tin oxide or reduced tin and may have crystallized in the glasses rather than have been added

in their present form. Long crystals consisting of silicon and calcium, probably in the form of the mineral wollastonite, were also noted in several of the reds. One of the reds (table 1, no. 36) also contained a large metallic inclusion that consisted of about 90 percent copper with relatively large amounts of arsenic and antimony (4–5 percent), traces of nickel and silver (approximately 0.3 percent), and small traces of tin, lead, and zinc (less than 0.1 percent).

The three red bracelet fragments (table 1, nos. B1–3) have compositions different from those of the red tesserae. Unlike the tesserae, none of the bracelet fragments contained any significant amount of lead, although a trace was found in B3. Like the tesserae, all three have soda-lime-silica compositions. However, these three glasses have larger amounts of magnesia and potash. Items B1 and B2 are very similar in composition, and contain more lime as well, greater than 10 percent, more than any of the other reds analyzed here. These two glasses also contain unusually high levels of strontium oxide, more than 0.2 percent, while the strontium values found for the tesserae ranged from 0.02 percent to a maximum value of 0.09 percent. The third bracelet fragment, B3, had slightly more strontium than observed in any of the mosaic tesserae, although not as much as in B1 and B2. The first two bracelet fragments were also somewhat unusual in having very low levels of chlorine present, less than 0.2 percent, whereas typical values for ancient soda glass usually range from about 0.5 to 1.5 percent. Like the red tesserae, these three reds are colored and opacified by copper oxide, although B3 contains much more copper than any of the red tesserae. Elevated iron levels were also found in the three bracelet fragments, as in the red tesserae, although the amount present in B2 is much higher than in any of the red tesserae.

The vessel fragment (table 1, V1) was, however, found to be similar in its overall composition to that found for the red tesserae, except for containing much less lead oxide, only about 1 percent compared to 6 to about 11 percent in the red tesserae. This red differed from the red tesserae, however, in containing somewhat less iron and considerably less copper than any of the red tesserae or the bracelet fragments. The bracelet fragments and the vessel fragment all differed from the red tesserae in several other ways. None of these fragments contains anywhere near the amounts of tin oxide found in the red tesserae, although traces of tin were detected in one of the bracelet fragments and in the vessel fragment. Also, only small traces of zinc were found in two of the fragments, compared to the nearly 1 percent zinc oxide found in all of the red tesserae. Small traces of cobalt, nickel, and arsenic were also noted in the red tesserae, but not found in any of the four red fragments. The vessel fragment



**Fig. 5** Scanning electron micrograph of a cross-sectioned sample of red glass showing large cubic tin oxide crystals and submicron cuprite crystallites (original magnification 7,500 $\times$ ).

analyzed here appears to fit into a group of vessel fragments previously analyzed from Amorium, many of which were described as dichroic.<sup>3</sup> One distinguishing feature of this group of glasses is the low levels of copper found, much lower than in the red tesserae or in the bracelet fragments.

EDS analysis of the gold leaf from one of the amber tesserae (table 1, no. 24) found the gold alloy to be relatively pure, with more than 99 percent gold by weight and less than 1 percent silver, with no detectable copper. The use of silver was confirmed by EDS analysis on the three bottle green tesserae, although most of the silver now appears to be present as black silver sulfide (Ag<sub>2</sub>S).

## Discussion

The compositions of all the glass tesserae analyzed here are consistent with the type of glass composition sometimes called “natron glass,” since it is thought to have been produced using natron from Egypt. This type of glass was the one most commonly used throughout the Mediterranean world and Europe from about the middle of the first millennium BCE through the ninth century CE.<sup>4</sup> Ancient documentary sources such as Pliny the Elder, as well as modern analytical studies, strongly suggest that this type of glass was produced using natron, a naturally occurring source of sodium that consists mainly of the mineral trona, a form of sodium carbonate, as the source of the fluxing agent for the glass. The other main ingredients of the glass were added in the form of sand that contained significant amounts of lime, or possibly may have had lime intentionally added. Natron glass typically contains a large amount of soda, usually about 15 to 20 percent by weight, along with about 5 to 10 percent lime, and low levels of magnesia and potash, generally about 0.5 percent to no more than 1.5 percent. Alumina is generally rather high, typically about 2 to 3 percent, but many examples have been found containing less than 2 percent or considerably more than 3 percent.

Analytical studies of Roman and Byzantine mosaic glass used during the first millennium CE have shown that natron-type glass was also the predominant type of glass used in tesserae production, although some tesserae, mainly shades of reds and orange, have been found with higher levels of magnesium and potassium than normally associated with natron glass.<sup>5</sup> Roman glass tesserae through the fourth century CE generally contain calcium antimonate crystals as an opacifying agent, with yellow and green opaque tesserae containing lead antimonate yellow crystals instead. During the fourth century, antimonate compounds were gradually replaced by tin compounds for opacifiers; tin oxide as a white opacifier and lead-tin yellow for opaque yellows and greens. The detection of antimony compounds in glasses dated after about the fourth century CE is usually thought to be evidence of reuse of Roman period glass. One must be careful, however, as the use of lead antimonate yellow has been documented in European Renaissance period vitreous materials, and calcium antimony also was used again as an opacifier possibly as early as the seventeenth century, and definitely during the nineteenth century.<sup>6</sup>

Early Byzantine period glass tesserae differ from those of the Roman period mainly in the use of lead-tin yellow rather than lead antimonate in yellow and green opaque tesserae. Whereas the majority of Roman tesserae are opaque, the majority of Byzantine tesserae appear to be translucent. Some have been reported to be somewhat opacified with features such as bubbles in the glass, as in the turquoise glasses in this study, or by the addition of quartz crystals, as reported for tesserae dated to the tenth century from Hosios Loukas.<sup>7</sup> Such features break up the light passing through the glass, making it appear turbid

3 M. T. Wypyski, “The Amorium Dichroic Glass Fragments: Technical Analyses,” in Gill, *Amorium*, 1:256–58.

4 I. Freestone, “Looking into Glass,” in *Science and the Past*, ed. S. Bowman (Toronto, 1991), 37–56; R. H. Brill, “Scientific Investigations of the Jalame Glass and Related Finds,” in *Excavations at Jalame: Site of a Glass Factory in Late Roman Palestine*, ed. G. Weinberg (Columbia, Mo., 1988), 257–94.

5 J. Henderson, “Chemical Characterization of Roman Glass Vessels, Enamels and Tesserae,” in *Materials Issues in Art and Archaeology*, Materials Research Society Symposium Proceedings 185 (Pittsburgh, 1991), 2:601–7; J. L. Mass, R. E. Stone, and M. T. Wypyski, “The Mineralogical and Metallurgical Origins of Roman Opaque Colored Glasses,” in *Prehistory and History of Glassmaking Technology*, ed. P. McCray, Ceramics and Civilization 8 (Westerville, Ohio, 1998), 121–44; M. T. Wypyski and L. Becker, “Glassmaking Technology at Antioch: Evidence from the Atrium House *Triclinium* and Later Mosaics,” in *The Arts of Antioch*, ed. L. Becker and C. Kondoleon (Worcester, Mass., 2005), 115–36; I. C. Freestone, M. Bimson, and D. Buckton, “Compositional Categories of Byzantine Glass Tesserae,” in *Annales du 11e congrès de l'Association internationale pour l'histoire du verre* (Amsterdam, 1990), 271–79; R. H. Brill, *Chemical Analyses of Early Glasses*, vol. 2, *Tables of Analyses* (Corning, N.Y., 1999).

6 M. T. Wypyski, “Renaissance Enameled Jewelry and 19th Century Renaissance Revival: Characterization of Enamel Compositions,” *Materials Issues in Art and Archaeology*, Materials Research Society Symposium Proceedings 712 (Warrendale, Pa., 2002), 6:223–33; J.-A. Page, L. Pilosi, and M. T. Wypyski, “Ancient Mosaic Glass or Modern Reproductions?” *JGS* 43 (2001): 115–39.

7 Freestone et. al., “Byzantine Glass Tesserae,” 275–76.

or cloudy without making it technically opaque. Although many examples have been reported of Byzantine mosaic tesserae containing lead and tin in opaque yellows and greens, presumably mostly present in the form of lead-tin yellow crystals, little evidence exists for the intentional use of tin oxide as a white opacifier in glass tesserae from the fifth century through the tenth century. Although lead-tin yellow was discovered in the opaque green tesserae from Amorium, and relatively large amounts of tin were found in the red tesserae, none of the tesserae was opacified with tin oxide.

Beginning in the tenth century, some Byzantine tesserae were first produced from a different type of glass. Data on mosaic tesserae from Hosios Loukas in central Greece revealed that mainly soda-lime-silica glass with relatively high levels of magnesium and potassium was used there.<sup>8</sup> However, all the blue glass reported is of the low magnesium, low potassium type and appears to come from another source. Analyses of tesserae from the eleventh-century mosaics from the monastery at Daphni near Athens and mosaics dated from the eleventh to the thirteenth century at San Marco in Venice also show similar levels of magnesium and potassium.<sup>9</sup> This type of soda-lime-silica glass is thought to have been produced using soda-rich plant ash containing significant amounts of magnesium and potassium, as well as calcium, rather than natron as the main source of alkali. Moreover, this type of glass is perhaps best known from studies of early Egyptian and Islamic glass. Some of the glasses reported from San Marco have very high levels of potash and phosphorus as well and appear to have been made using wood ash. Glass made from wood ash is typical of northern European production from about the tenth century to the Renaissance. Whereas none of the glass reported from Hosios Loukas or Daphni appears to contain any significant amounts of tin, nor to contain tin-based opacifiers, some of the tesserae from San Marco contain significant amounts of tin and appear to contain either tin oxide or lead-tin yellow opacifier.

Not all of the glasses reported from the tenth century or later, however, are of the high-magnesium, high-potassium plant ash type of composition. Mosaic tesserae from Torcello, for example, dated from the eleventh to twelfth century, and tesserae from San Clemente in Rome, dated to the twelfth century, were nearly all found to have low magnesium and potassium compositions and appear to be natron glass (some of the tesserae from San Clemente have unusual compositions, however, but these may all date to restoration done in the 18th century).<sup>10</sup> Many of these later natron-type glasses, including the tesserae analyzed from San Clemente, contain significant amounts of antimony, probably present as calcium antimonate white or lead antimonate yellow opacifier. As antimony compounds are not known from glass production during this period, these tesserae probably represent the recycling of Roman-period tesserae or other glass. The reuse of early glass has been documented for medieval enamels on metal and in the production of some window glass as well.<sup>11</sup> It also probably occurred in mosaics. Some of the earliest Byzantine mosaics, including several from Ravenna dated to the sixth century, and mosaics from the basilica of Sts. Cosmas and Damian in Rome, dated to the sixth and seventh centuries, also contain many examples of tesserae that appear to have been reused from the Roman period.<sup>12</sup>

Recent work by I. C. Freestone and others has recognized at least five production groups of primary natron-based glass in use from about the fourth to ninth centuries CE.<sup>13</sup> These groups were identified through comparison of the relative amounts of the major elements present, particularly the amounts of lime and alumina, and the ratios of certain trace elements, particularly the rare

8 Ibid., 277; Brill, *Chemical Analyses*, 224.

9 C. Fiori et al., "Compositional and Technological Characteristics of Glass Tesserae from the Vault Mosaics of Dafni Monastery, Greece," in *Hyalos = Vitrum = Glass: History, Technology and Conservation of Glass and Vitreous Materials in the Hellenic World*, ed. G. Kordas (Athens, 2002), 193–97; Brill, *Chemical Analyses*, 225–26.

10 Ibid., 227, 232–35.

11 I. C. Freestone, "Theophilus and the Composition of Medieval Glass," in *Materials Issues in Art and Archaeology*, Materials Research Society Proceedings 267 (Pittsburgh, 1992), 3:739–45; I. Biron, P. Dandridge, and M. T. Wypyski, "Techniques and Materials in Limoges Enamels," in *The Enamels of Limoges: 1100–1350*, ed. B. Boehm and E. Taburet-Delahaye (New York, 1996), 48–62 and 445–50.

12 Brill, *Chemical Analyses*, 220–21; I. Roncuzzi-Fiorentini and C. Fiori, "Applicazione dell'analisi chimica allo studio del vetro musivo bizantino del V–VI secolo," *Mosaico e restauro musivo* 5 (1989): 9–57; M. Verità, B. Profilo, and M. Vallotto, "I mosaici della basilica dei Santi Cosma e Damiano a Roma: Studi analitico delle tessere vitree," *Revista della Stazione Sperimentale del Vetro* 32 (2002): 13–34.

13 "Primary Glass Sources in the Mid First Millennium AD," in *Annales du 15e congrès de l'Association internationale pour l'histoire du verre* (Nottingham, 2003), 111–15.



earth elements such as lanthanum and cerium. Although it is not possible to look at the amounts of most of these trace elements with the analytical method used in this study, comparison of the major elements in the Amorium tesserae suggests that many of them belong to the group identified as Levantine I, while some may belong to the group known as Egypt II. Levantine I glass appears to have been the typical glass of the Levant from the fourth to the seventh century, while Egypt II glass is associated with Egyptian production during the eighth to ninth centuries. The majority of the glasses from Maroni Petrera, Cyprus, dated from the sixth to seventh centuries, have also recently been identified as being of the Levantine I type.<sup>14</sup>

As noted above, the condition of some of the gold-covered tesserae has led to speculation that they, and possibly others from the site, had been recycled from earlier existing mosaics. The possible identification of glass of the Levantine I type used in the production of the Amorium tesserae may also be evidence that the tesserae were produced no later than the seventh century and must have been reused. However, identification of primary glass production sites is somewhat problematical, particularly for colored glass, where the incorporation of unintentional elements added along with the source of the colorants may distort the relative amounts of the major and trace elements used to distinguish the glass groups. Recycling and mixing of different types of glass can also disguise the primary glass sources. Furthermore, it is by no means certain that production of Levantine I glass stopped after the seventh century, but the best estimates so far from available data are that it was produced from only the fourth to the seventh century.

Examination of the data in table 1 for all eight of the gold-covered tesserae analyzed also shows that only two different glasses were used, distinguished from each other mainly by small differences in the amounts of soda and lime found. Two of the undamaged gold tesserae (table 1, nos. 24, 25) are essentially identical to each other and to one of the molten-cover ones (table 1, no. 29). The other two undamaged gold tesserae (table 1, nos. 26, 27) appear to form another group with the other three molten-cover gold tesserae (table 1, nos. 28, 30, 31). Thus it appears that if the molten-cover tesserae were recycled, the other gold tesserae, and possibly others as well, may also have come from an existing mosaic. Gold-covered tesserae with compositions very similar to these have also been reported from San Vitale and Sant'Apollinare in Classe in Ravenna and from Petra, Jordan, dating from the sixth century.<sup>15</sup>

The red tesserae are particularly interesting in having unusual amounts of tin and zinc. Although many different red opaque glasses from different places and times have been found to contain traces of both, the relatively high levels found in the Amorium red tesserae are unique. Some of the red tesserae from Beth Shean (ancient Skythopolis), Israel, dated to the fifth century, have similar compositions to the Amorium reds, although the ones reported from Beth Shean contain somewhat lower levels of lead and tin than do those found in most of the Amorium reds.<sup>16</sup> Two red tesserae from St. Demetrios in Thessalonike, dated to the ninth century, have also been reported that are similar to the Amorium reds, although again the amount of tin found in these glasses is less than at Amorium.<sup>17</sup> Traces of cobalt, nickel, and arsenic were noted in the Amorium reds as well, and traces of cobalt and nickel were also reported in the St. Demetrios red tesserae, although the presence or absence of arsenic was not reported. Arsenic was not detected in the tesserae from Beth Shean, and nickel and cobalt were apparently not sought in the analyses (this may have been due, however, to peak overlap in the spectra which raised the

14 I. C. Freestone, M. Ponting, and M. J. Hughes, "The Origins of Byzantine Glass from Maroni Petrera, Cyprus," *Archaeometry* 44, no. 2 (2002): 257–72.

15 Roncuzzi-Fiorentini and Fiori, "Applicazione," 51.

16 A. N. Shugar, "Byzantine Opaque Red Glass Tesserae from Beit Shean, Israel," *Archaeometry* 42, no. 2 (2000): 375–84.

17 Brill, *Chemical Analyses*, 229.

minimum detection limits for arsenic above that of the very small amounts determined for the Amorium reds).

The small amounts of tin found in the translucent copper-colored glasses were in a ratio of approximately one to ten with copper, suggesting that, as others have observed, the source of the copper used to color the glass may have been a bronze alloy. The ratio of tin to copper in the red tesserae, however, ranges from about one to one to greater than two to one. The production of red glass is technically demanding, requiring reducing conditions in the glass melt to produce the reduced red form of copper oxide.<sup>18</sup> The large amounts of tin found in the reds suggests that tin was added separately to the glass, perhaps to aid in the reduction of the copper oxide to the red cuprite. The ratio of zinc to copper oxide is also rather high in these glasses, possibly suggesting the intentional addition of some form of zinc as well. The presence of the zinc, however, may be due to the use of a brass as the source of the copper in the glass, unlike the mixture in the turquoise glasses. The traces of nickel and arsenic may also have come from the source of the added copper.

### Conclusions

This study was done to provide data on the compositions of the glass mosaic tesserae from the Amorium site for comparison with other Byzantine mosaics as well as with some of the other types of glass found on site. The data indicate that the chemical compositions of the tesserae from these mosaics are more closely related to the majority of glass dating from before the tenth century, rather than that generally found from the tenth century or later. Some evidence was found in the overall compositions of the majority of the glasses that suggests that they may date earlier than the time of about 900 CE given for the production of the mosaics from the site, which would corroborate the physical evidence of some of the tesserae found. However, this can be considered as only a possibility at the moment, until further research is done. No direct evidence of the reuse of older Roman glass in the form of antimony compounds, however, was found in the Amorium tesserae, although it has been observed in many other Byzantine mosaics.

Red glass from the site was of interest because three different types of glass were used for as many different functions, and each glass was slightly unusual in its own way. Further work may show which, if any, of the glasses were produced at Amorium or imported from elsewhere.

—*Department of Scientific Research*  
*The Metropolitan Museum of Art*

I am grateful to Christopher Lightfoot, associate curator, Department of Greek and Roman Art, The Metropolitan Museum of Art, for inviting me to work on this project. Many thanks are also due to Ian Freestone, professor, Cardiff University, for generously sharing his many insights into glass compositional studies. I would also like to extend my thanks to Lisa Pilosi, Department of Objects Conservation, The Metropolitan Museum of Art, for her continued support and encouragement for this and many other projects.

18 I. C. Freestone, "Composition and Microstructure of Early Opaque Red Glass," in *Early Vitreous Materials*, ed. M. Bimson and I. C. Freestone, British Museum Occasional Paper 56 (London, 1987), 173–91; R. H. Brill and N. D. Cahill, "A Red Opaque from Sardis and Some Thoughts on Red Opaques in General," *JGS* 30 (1988): 16–27; I. C. Freestone, C. P. Stapleton, and V. Rigby, "The Production of Red Glass and Enamel in the Late Iron Age, Roman and Byzantine Periods," in *Through a Glass Brightly: Studies in Byzantine and Medieval Art and Archaeology Presented to David Buckton*, ed. C. Entwistle (Oxford, 2003), 142–54.